Erratum: algebraic spin liquid as the mother of many competing orders

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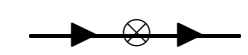
We correct an error in our paper Phys. Rev. B 72, 104404 (2005) [cond-mat/0502215]. We show that a particular fermion bilinear is not related to the other "competing orders" of the algebraic spin liquid, and does not possess their slowly decaying correlations. For the square lattice staggered flux spin liquid (equivalently, d-wave RVB state), this observable corresponds to the uniform spin chirality.

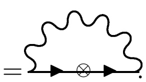
In a recent paper,[1] we studied the staggered flux algebraic spin liquid state of the square lattice $S = 1/2$ Heisenberg antiferromagnet. We emphasized the presence of an SU(4) emergent symmetry present at low energy in this state, and showed that it leads to a striking unification of several seemingly unrelated "competing orders," including order parameters for the Neel and valence bond solid states. In the field theory of the algebraic spin liquid, which consists of $N_f = 4$ two-component Dirac fermions coupled to a U(1) gauge field, these competing orders arise as a set of fermion bilinears transforming in the adjoint representation of SU(4): $N^a = \Psi^\dagger \tau^3 T^a \Psi$. These observables exhibit slow power law correlations, characterized by the power law decay $\langle N^a(\boldsymbol{r}) N^b(0)\rangle \sim \delta_{ab}/|\boldsymbol{r}|^{2\Delta_N}$, where one expects Δ_N is smaller than its large-N_f (or mean field) value of 2. This expectation is based on the result of Rantner and Wen that $\Delta_N = 2 - 64/(3\pi^2 N_f) + \mathcal{O}(1/N_f^2)$,[2] as well as the physical picture that the U(1) gauge force tends to bind the oppositely charged Ψ and $\Psi^\dagger$ fermions together. This makes the mode created by N^a propagate more like a single particle-like boson, as opposed to a composite of two free fermions, thus reducing Δ_N. This tendency increases as N_f is decreased, which reduces the screening of the gauge field and leads to a stronger gauge interaction between fermions.

In Ref. 1, we claimed that the SU(4) singlet $M = \Psi^\dagger \tau^3 \Psi$ has the same power law decay as N^a, that is $\langle M(\boldsymbol{r}) M(0)\rangle \sim 1/|\boldsymbol{r}|^{2\Delta_M}$, where $\Delta_M = \Delta_N$ to all orders in the $1/N_f$ expansion. However, our argument in Appendix D of Ref. 1 missed an important class of diagrams, and as a result this statement is not correct. In fact, Δ_M and Δ_N differ at order $1/N_f$. Here, we outline the calculation of Δ_M to this order. The result is $\Delta_M = 2 + 128/(3\pi^2 N_f) + \mathcal{O}(1/N_f^2)$. Next, we discuss this result in the context of the physical picture of gauge binding given above.

We calculate Δ_M by adding mM as a perturbation to the action, and examining its leading order contribution to the fermion Green's function; this is along the same lines as the calculation of the scaling dimension of velocity anisotropy in Appendix C of Ref. 1. The vertex corresponding to insertion of M is denoted by

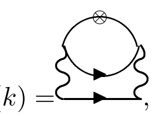
 $= im. \quad (1)$

We consider the term in the fermion self-energy of first order in both $1/N_f$ and in m, denoted $\Sigma(k) = \sum_{i=1}^{3} \Sigma_i(k)$. We have

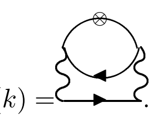
$\Sigma_1(k) =$  $. \quad (2)$

A corresponding diagram is also present for N^a, and leads to the result of Ref. 2.

In addition, we have

$\Sigma_2(k) =$  $, \quad (3)$

and

$\Sigma_3(k) =$  $. \quad (4)$

These diagrams, which were missed by us in Ref. 1, only contribute to Δ_M; the corresponding diagrams for N^a vanish because the fermion loop involves a trace over a single SU(4) generator.

These diagrams can be evaluated using dimensional regularization, as in Appendix C of Ref. 1. Keeping only the logarithmically divergent parts, we have

$$\Sigma_1(k) = -\frac{24}{\pi^2 N_f}(im)\ln\Big(\frac{|k|}{\mu}\Big) \quad (5)$$

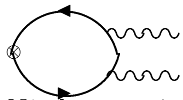
$$\Sigma_2(k) = \Sigma_3(k) = \frac{32}{\pi^2 N_f}(im)\ln\Big(\frac{|k|}{\mu}\Big). \quad (6)$$

Applying the Callan-Symanzik equation as described in Ref. 1, we find

$$\Delta_M = 2 + \frac{128}{3\pi^2 N_f} + \mathcal{O}(1/N_f^2). \quad (7)$$

It is perhaps surprising that Δ_M has *increased* above its $N_f \to \infty$ value, because this seems to call into question the validity of the physical picture that gauge binding should lower the scaling dimension. However, there is

an important difference between the N^a and M fermion bilinears. The M fermion bilinear can decay into photons, as represented by the diagram


. (8)

This is impossible for N^a, because it carries the SU(4) flavor quantum number. Such decay processes will reduce the ability of the mode created by $\Psi^\dagger \tau^3 \Psi$ to propagate as a single particle-like object, and thus compete against the binding due to the gauge force. Evidently, at least at large-N_f the decay processes win out over the gauge binding, and Δ_M is increased above the value for noninteracting fermions. Because no similar decay process is allowed for N^a, we still expect $\Delta_N < 2$ for all values of N_f.

We would like to thank Subir Sachdev for bringing this error to our attention.

[1] M. Hermele, T. Senthil, and M. P. A. Fisher, Phys. Rev. B **72**, 104404 (2005).
[2] W. Rantner and X.-G. Wen, Phys. Rev. B **66**, 144501 (2002).